Parameter Analysis and Contrail Detection of Aircraft Engine Simulations

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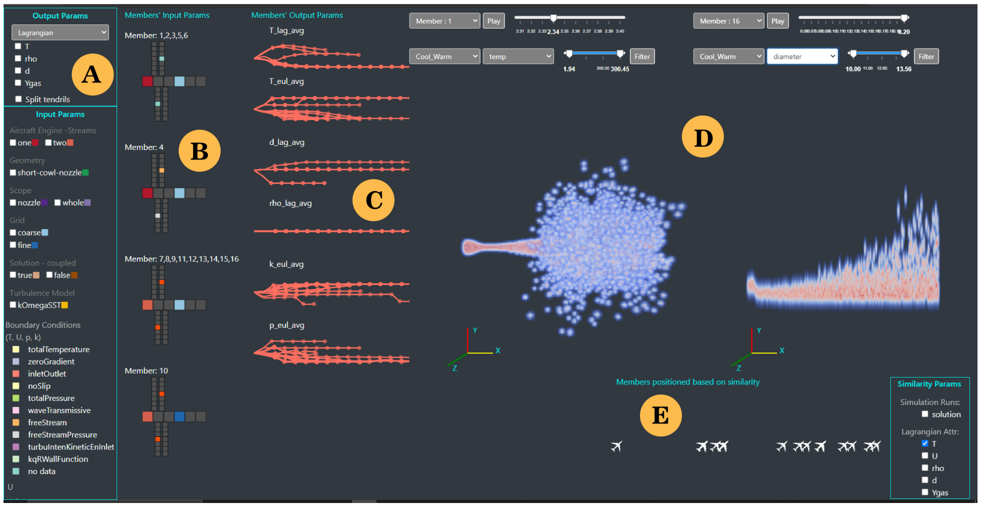

Figure 1: Visual interface of aircraft engine simulation analysis: **(A)** Legend and filters panel for input and output parameters of the simulation ensembles. **(B)** Custom encoding grouping members based on the simulation input parameter values. **(C)** Filament plots for output parameters that group output parameters of all ensemble members. Each filament indicates the temporal parameter change of each ensemble member. **(D)** 3D views of 2 ensemble members that show the evolution of the engine particles trajectories over time. **(E)** 2D projection of all ensemble members based on the Principal Component Analysis of a predefined list of simulation parameters.

Abstract

Aircraft engines emit particulates that alter the chemical composition of the atmosphere and perturb the Earth's radiation budget by creating additional ice clouds in the form of condensation trails called contrails. We propose a multi-scale visual computing system that will assist in defining contrail features with parameter analysis for computer-generated aircraft engine simulations. These simulations are computationally intensive and rely on high performance computing (HPC) solutions. Our multi-linked visual system seeks to help in the identification of the formation and evolution of contrails and in the identification of contrail-related spatial features from the simulation workflow.

1 Introduction

The question of how and to which extent contrails contribute to climate change has been a matter of debate and concern among scientists over the last two decades [8]. Contrails form by condensation of water vapor onto suitable particulates under sufficiently low ambient temperature, and can spread in supersaturated ambient conditions over areas of several square kilometers.

The formation of contrails and their evolution over time are often analyzed by scientists through HPC computer-generated airplane engine simulations. These simulations are run with different input parameter values and boundary conditions to generate spatio-temporal outputs. The output data, referred to as ensemble data, is large scale, multi-variate, multi-dimensional, and spatio-temporal, hence difficult to analyze.

We propose a visual computing framework for the analysis of multiple airplane engine simulation runs at multiple levels. Our system aims to help domain experts study the simulations' parameter evolution, particles' attributes and trajectories, and detect and further study the formation and evolution of contrails.

2 Related Work

Paoli et al. [7] have studied contrail formation in the first few seconds after engine emission and observed that in lower temperature and adequate availability of water vapor, contrails start to form at the edge of the engine. Most visualization techniques that analyze and explore ensemble datasets [9] aim to identify areas of interest and quantify uncertainty across multiple outcomes. However, the analysis is often focused on providing a summary of the ensemble data in terms of mean and standard deviation values while discarding lower-level features [6]. In contrast, our project seeks to enable analysis at multiple scales, from individual spatial features to feature evolution over time.

Our project was inspired by the work of Luciani et al. [4], who used multi-linked views to support the exploration of multi-run ensemble simulations. However, they neither take into consideration the correlation between input and output parameters, nor compare multiple ensemble members at the same time. On the other hand, Dahshan et al. [1] tried to minimize the gap between parameter and ensemble space by combining input parameters and simulation outputs in order to interpret similarities between ensemble members. However, their work does not support in-depth knowledge about simulation particles and their temporal trajectories.

The temporal nature of the ensemble data often makes it difficult to explore. The tendril plot [3], a novel tool for analyzing medical

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temporal data, is a great way to find trends and anomalies between sequential temporal data. We used a customized tendril plot, namely the filament plot, to visualize our temporal parameter ensemble data.

3 Data and Design

Data: Procuring the data for an ensemble member can take up to several days and high-performance computing power to extract relevant information. The data is huge ($> 100GB$) and the sources of information are multiple computer-generated aircraft engine particle simulations. Each simulation model was run with slightly different user-defined input parameter settings and boundary conditions to generate multiple ensemble members. Each ensemble member consisted of multiple time steps, and each time step had multiple attributes of the engine particles, including position, temperature, diameter, ice label, and pressure.

Design: Our interdisciplinary collaboration followed an activity centered design paradigm [5]. The paradigm is an extension of human-centered-design, with emphasis on user activities and workflow. Through multiple iterations, we met with the end users to define functional specifications, prototype the interface, evaluate prototypes, and decide on changes in the specifications.

Our proposed system incorporates multiple linked views that provides a thorough understanding of the predefined parameters and temporal evolution of the particle simulations, providing both overview and detail. The interface consists of three main views: 1) the Input and Output Parameters View (Fig. 1.A,B,C), the 3D Airplane Engine Projection View (Fig. 1.D), and the Ensemble Member Similarities View (Fig. 1.E).

Input and Output Parameters View. This view aims to be a guided summary and comparison of all of the ensemble members to identify areas of interest across multiple simulation runs, select and examine specific ensemble members with the help of input and output parameter values. Dealing with a large number of input parameters, we used a customized airplane-shaped heatmap (Fig. 1.B) that groups members with identical input attributes. Each attribute has dedicated colored sections, however, each heatmap is only colored for the parameters whose values differ across members. The output parameters are sequential event-based attributes. We calculated average values per timestep for each output parameter. One plot for each output parameter groups the temporal value of all ensemble members in a tendril plot-inspired view [3], called a filament plot (Fig. 1.C) [2]. The curvature of a filament encodes the relative change from the previous value, with upward rotation showing a value increase in the parameter temporal evolution.

3D Airplane Engine Projection View. This view is used to analyze the 3D simulation of two ensemble members over time, emphasizing the spatial features, formation, and evolution of the contrails (Fig. 1.D). As each simulation can contain upto millions of particles, the rendering time can affect the efficiency of the system. Therefore, to efficiently show the detailed distribution of the ensemble data without compromising any important information, we have incorporated the volume rendering technique in our system. First, we applied Gaussian resampling to the particle data to convert them into volumetric data. Multiple parameters such as temperature, diameter, ice label were used to calculate the density distributions of the particle data. After extracting the volumetric data, we applied a direct volume rendering technique (Volume Ray Casting), which provided better image quality than other methods. This view allows the analysis of the distribution of particles over time, color-coded based on the list of preselected attributes. Additionally, animations of all simulation runs are available, as well as filters for the particles' chemical properties.

Ensemble Member Similarities View. To emphasize similar members according to the input and output parameters and present an overview of their correlation, this view (Fig. 1.D) uses the Principal Component Analysis (PCA) projection to accentuate groups of similar members and outliers based on selected parameters.

4 Evaluation

We conducted a qualitative evaluation with the domain expert and one mechanical graduate student. The evaluators asked questions to direct the exploration, and provided feedback.

The multi-linked views consisting of input-output parameter panel, heatmaps, filament plots and 3D airplane engine projection views yielded enthusiastic feedback. Most of the times, domain experts want to find similar ensemble members to investigate the relevant parameter settings, boundary conditions and compare the simulation outputs. The ability to filter ensemble members based on their input and output parameters using the airplane shaped heatmaps and filament plots was considered very helpful to assess their similarities. In addition to that, the PCA projection assisted the domain expert to understand the outliers between the ensemble members.

In a real-life scenario, contrails start to form little further from the aircraft engine when the particles come into contact with water vapor at a relatively lower temperature. From the 3D view, it was clear that the simulation-generated contrails followed the same pattern. Additionally, by using the animation feature, the domain expert was able to understand the contrail evolution over time, which supported his intuition about its formation and evolution.

5 Discussion and Conclusion

Our interactive visual analysis system links 3D simulation visualization techniques with parameters details of ensemble members in order to explore trends and anomalies within the data, as well as to detect and analyze formation and evolution of contrails.

Future work will include members' comparison, the manipulation of input and output parameters to find ways to minimize the formation of the contrails, and supporting the automatic detection and tracking of contrail-related spatial features.

Acknowledgments

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